# Ocean Variability Effects on Underwater Acoustic Communications

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## LONG-TERM GOALS

This proposed research seeks to identify, explain, and ultimately predict, the factors that significantly alter the operational effectiveness of underwater acoustic communications through experimental work and theoretical analysis. The long-term goal is to develop reliable, high rate transceivers customized for coherent underwater acoustic communications.

## OBJECTIVES

The research objective is to investigate the relationship between environmental fluctuations and the performance of coherent underwater acoustic communications at high frequencies (8-50 kHz) through experimental research and data analysis. High rate communication methods are to be developed based on the understanding of acoustic propagation physics in dynamic shallow water environments.

## APPROACH

In a dynamic ocean environment, two types of channel fluctuations critical to high data rate coherent acoustic communications are considered: Rapid fluctuations of the channel over scales of seconds and long-term channel variations over scales of hours [1-2]. During the past few years, we have fielded multiple high frequency acoustic communication experiments [3-6]. Based on the experimental work, reliable, low-complexity algorithms have been developed for single- and multiple-source acoustic communications in a dynamic ocean environment [2, 7]. For multiple-source systems, or multiple-input/multiple-output (MIMO) systems, decision feedback equalization and interference cancellation schemes have been integrated in time reversal processing. Time reversal processing leads to low-complexity. Decision feedback equalization further compensates for the ISI. The incorporated interference cancellation scheme suppresses the co-channel interference (CoI), or cross-talk. Frequent channel estimation is used to deal with time-varying acoustic propagation in a dynamic ocean. The

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MIMO receiver also iterates channel estimation and symbol demodulation with interference cancellation to achieve improved communication performance.

**WORK COMPLETED**

1) Participation in KAM11. The University of Delaware (UDEL) team provided acoustic transmissions and reception capabilities as well as environmental sensors to the experiment. For example, a tripod receiving array was deployed multiple times as part of communication experiments, where two source arrays and multiple receiving arrays were deployed. Two tripod transceivers were also deployed twice for reciprocal acoustic transmissions with Waverider and video camera monitoring surface waves.

2) Data analysis of KAM08 and KAM11 data. We continued our receiver design efforts aiming for practical, high data rate systems based on our experimental work. One aspect was to design proper transceivers for accessing wide frequency bands, using both single- and multiple-source systems.

**RESULTS**

The KAM11 experiment was conducted in Kauai, Island, Hawaii, from June 23 to July 12, 2011. During the three week research cruise, various communication signals were tested for different frequencies, source-receiver settings, and ocean conditions. Along with the acoustic measurements, environmental data were collected including wind, surface wave spectrum and images, and water column temperature profiles.

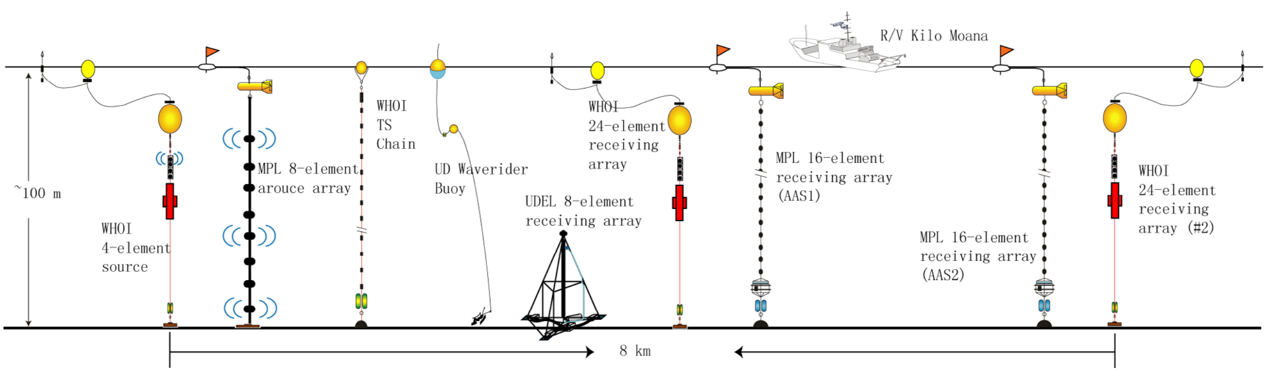
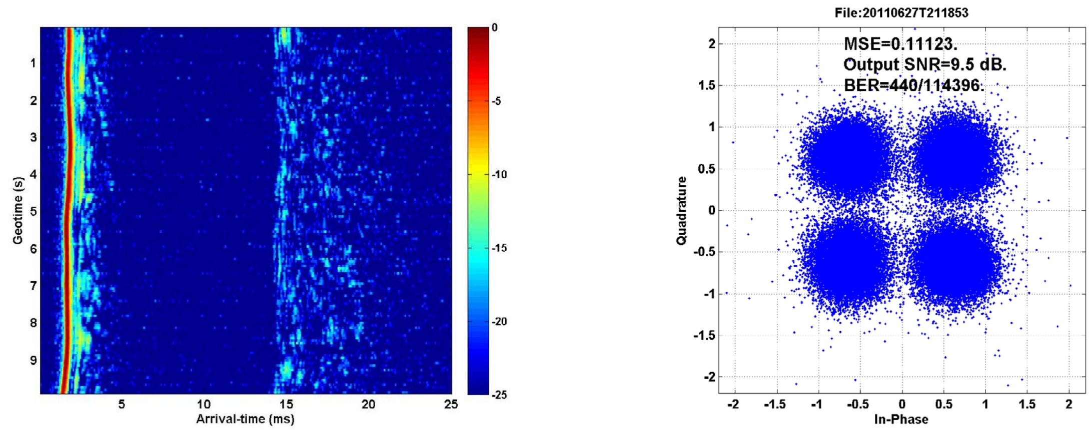



***Figure 1. Typical setting during KAM11***.

In one typical communication deployment as shown Fig. 1, two source arrays transmitted different communication waveform spanning from 9 kHz to 32 kHz. Five receiving arrays from three institutions were deployed along the 100 m isobath. The UDEL tripod receiving was mounted on the seafloor. As shown in Fig.1, the maximum communication range was 8 km for fixed-platform deployments. Multiple environmental sensors were deployed including thermistor strings and a Waverider Buoy. A video camera was installed on the R/V Kilo Moana to record surface waves. During some periods, ship-tethered, upper-ocean environmental monitoring frame was deployed to measure the sub-surface bubbles.

In addition to the communication experiments, two UDEL tripods were deployed for reciprocal transmission for our modeling efforts for two different times during KAM11. The objectives were to address the deterministic and statistical features of signal propagation affected by the thermocline and the surface wave dynamics, including temporal intensity fluctuations and refractive index and interference at various time scales.




(a) (b)

***Fig. 2. Time reversal experiment between the WHOI source and a small aperture 8-element UDEL receiver: (a) Impulse responses, and (b) Demodulation results. The source-receiver range was 2 km. The data rate achieved was 12 kilobits/s with a BER of 0.3%, at the carrier frequency of 12 kHz.***

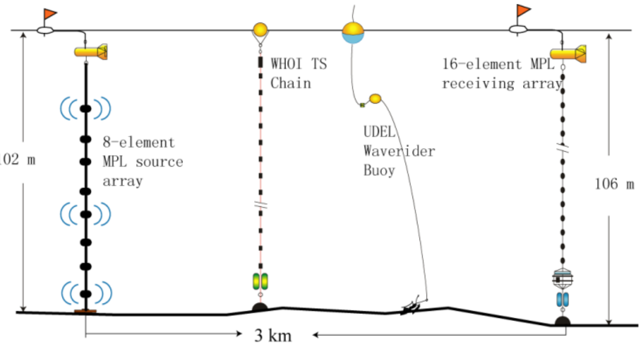
In the rest of this section, two examples are presented to show the communication results during KAM11. The first example demonstrates time reversal communications between a surface-zone source and a small aperture receiver during a rough surface condition. As shown in Fig. 1, a four-element WHOI source array was moored in the upper water column as the communication source. The bottom transducer at a nominal depth of 16.5 m was used as the source. The source level was 185 dB re 1 μPa at 1 m. An eight-element UDEL array was moored at 2 km range from the source array along the isobath as the communication receiver. The bottom element was positioned at 1 m above the seafloor. The element spacing was 0.5 m and, thus, the aperture was 3.5 m. The 8 second long quadrature phase shift keying (QPSK) signal with carrier frequency $f_c$=13 kHz was analyzed here. The communication sequence had a symbol rate of R=6 kHz. During the acoustic transmission, the sea surface was rough with a significant wave height of about 1.80 m. The wind speed collected from the R/V Kilo Moana was 12 m/s. The water column was well-mixed down below 80 m, indicated by temperature profiles collected at 1 km away from the receiving array and on the 100 m isobath.

Due to the rough surface condition and the source positioned in the mixed layer, dynamic channel characteristics were observed. As shown in Fig. 2(a), a strong return was shown before arrival time 5 ms. It was the constructive combination of direct and bottom paths. Even though the source was moored and the receiver was bottom mounted, the visible arrival time fluctuations were observed for this combined return. Around arrival time 15 ms, surface returns showed much weaker intensity due to scattering from the rough surface.

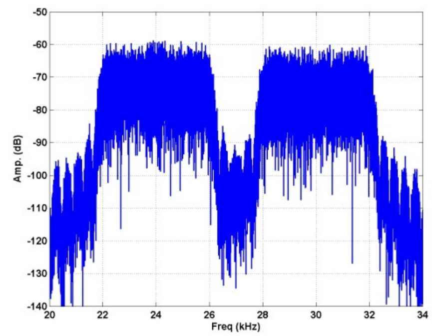
To deal with the time-varying impulse response, time reversal DFE with frequent channel estimation and phase tracking at individual hydrophones was applied. It was shown that the receiver performed best when using both phase tracking and sparse channel estimation at individual hydrophones. Matching pursuit channel estimation after phase tracking provided about 3 dB performance gain over the least squares algorithm without phase tracking. Under this configuration, the time reversal receiver demonstrated a data rate of 12 kilobits/s for the source-receiver range of 2 km, as shown in Fig. 2(b).

In addition to single source communications, wideband MIMO communications was tested. As shown in Fig. 3(a), the 8-element source array and the 16-elment receiving array from KAM08 were used in a similar configuration. The source array was moored during KAM11. The communication range was changed to 3 km. Two elements of the source array were used for MIMO transmissions. To utilize the transmission frequency band of 22-32 kHz, each source element transmitted QPSK signals at a symbol rate of 4 kHz for two sub-bands, referred to as low band and high band here. The low frequency band (21.75-26.25 kHz) centered at 24 kHz and the high band (27.75-32.25 kHz) at 30 kHz. There existed 1.5 kHz separation between the two bands. The spectrum of the transmitted QPSK signal is shown in Fig. 3(b). During the acoustic transmissions, the ocean had a thermocline at the depths of 50-60 m. The sea surface was relatively rough indicated by the measurement from the Waverider buoy, with a significant wave height of 1.07 m.

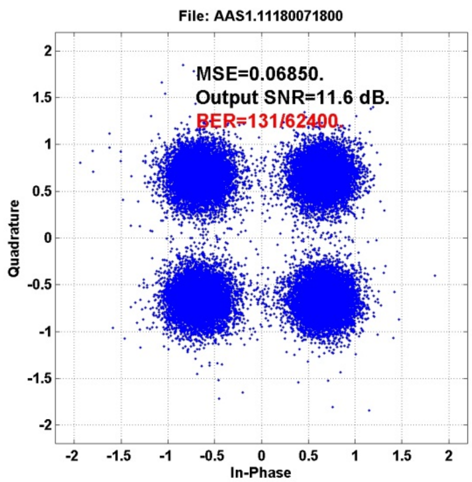
For each band, the time reversal MIMO receiver was applied with sparse channel estimation. At the low band, the demodulation results from the DFE soft output are shown in Figs. 3(c) and (d) for the first and second transducers, respectively. Figures 3(e) and (f) show the demodulation results for the high band. As shown, both band had low BERs over the two source elements: The low band had an average BER of 0.35% and the high band 0.39%. The total data rate was 32 kilobits/s using two transducers over the 10.5 kHz bandwidth. In the literature, a large number of efforts have been focused on orthogonal frequency-division multiplexing (OFDM) schemes for accessing wide frequency bands. Compared with OFDM schemes, the multiband MIMO transmission combined with time reversal processing provides both high spectral efficiency and low implementation transceiver complexity.



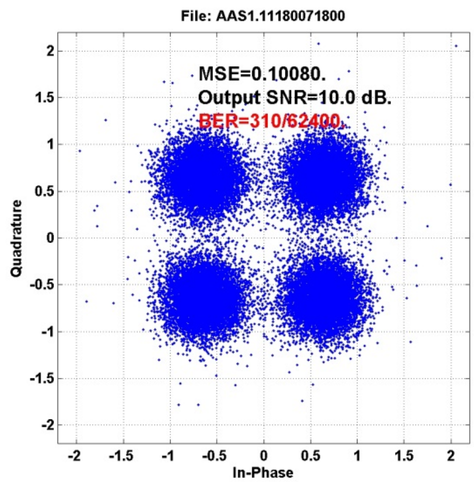

(a) Experimental setting



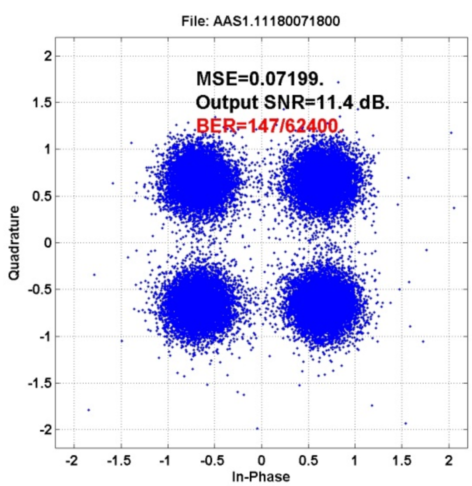

(b) Transmission spectrum



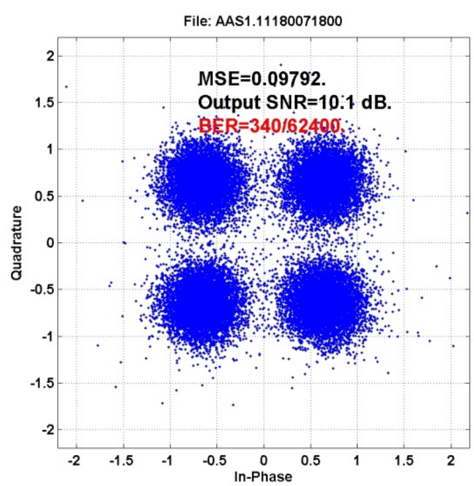

(c) Low band (21.75-26.25 kHz), Tx-1




(d) Low band (21.75-26.25 kHz), Tx-2




(e) High band (27.75-32.25 kHz), Tx-1




(f) High band (27.75-32.25 kHz), Tx-2

***Figure 3. Wideband MIMO communications during KAM11. Subplots (a) and (b) shows the experimental setting and the transmission spectrum. Subplots (c) and (d) show soft demodulation results at the low band for two transducers. Subplots (e) and (f) show demodulation results at the high band. The data rate achieved was 32 kilobits/s with a BER of 0.4%. The bandwidth used was 10.5 kHz***

## IMPACT/APPLICATIONS

The developed receiver is a low-complexity structure for robust, high data rate underwater digital communications at high frequencies. It can drastically improve data rates of underwater acoustic modems. The relationship between ocean environment fluctuations and acoustic modem performance can guide future modeling efforts.

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